Bismuth-Doped Fiber Amplifier Operating in the Spectrally Adjacent to EDFA Range of 1425-1500 nm

V.V. Dvoyrin[1,2], V.M. Mashinsky[3], S.K. Turitsyn[1,2]
[1]*Aston Institute of Photonic Technologies, Aston University, Birmingham B4 7ET, UK*
[2]*Aston-NSU Centre for Photonics,, Novosibirsk State University, Novosibirsk 630090, Russia*
[3]*Fiber Optics Research Center, RAS, 11933 Moscow, Russia*
v.dvoyrin@aston.ac.uk

Abstract: We demonstrate a Bi-doped fiber amplifier operating in the range of 1425-1500 nm with the maximum gain of 27.9 dB, the lowest noise figure of ~5 dB, and the maximum output power of 505 mW. © 2020 The Author(s)

1. Introduction

One of the promising intermediate-term solutions to cope with a rapid growth of telecommunication data traffic demands is to expand the operation range to the untapped spectral bands of the single-mode fiber (SMF). Implementation of this concept requires introduction of new telecom optical amplifiers in the optical bands complimentary to the existing Erbium-doped fiber amplifiers (EDFAs) [1]. Novel optical amplifiers operating, primarily, in S-band (1.46-1.53 μm) and E-band (1.36–1.46 μm) would be especially convenient for integration with the existing technology and telecom networks. Bi-doped fiber amplifiers are promising candidates because they are fully compatible with conventional silica-based telecommunication fibers. Several types of Bi-doped fiber amplifiers operating in different spectral domains have already been demonstrated [2-5]. Recently, we presented the multi-channel Bi-doped fiber amplifier compatible with a coarse wavelength-division multiplexing (CWDM) operating simultaneously at the wavelengths of 1430, 1450, 1470, and 1490 nm [6]. Current efforts in this field are focused on flattening the gain of the Bi-doped fiber amplifiers, reducing the noise figure and expanding their operation range further in the long-wavelength domain adjacent to the EDFA spectrum. Here we investigate a possibility of shifting the optical gain to longer wavelengths and demonstrate Bi-doped fiber amplifiers operating in the range of 1425-1500 nm, thus spectrally adjacent to the EDFAs.

2. Experimental Setup

For the amplifier, we used a 400-m long piece of the Bi-doped germanosilicate fiber with the core diameter of 12 μm and the cutoff at around 1.1 μm fabricated by the MCVD method. Two home-made fiber Raman converters producing radiation at the wavelength of 1330 and 1350 nm, respectively, with output optical power of up to 2.5 W each, have been used as optical pump sources. Earlier, a Bi-doped fiber amplifier had been optically pumped at the wavelength of 1305 nm [6], and we expected a "red" shift of the optical gain produced with these new pump wavelengths. The core absorption of the Bi-doped optical fiber at the pump wavelengths of 1330 and 1350 nm amounted to 39 and 54 dB, respectively. The scheme of the experiment is shown in Fig. 1a. A home-made Tm-doped-fiber-based ASE source emitting in the range of 1.42-1.5 microns was utilized as the signal source, which radiation intensity was modulated at ~100 Hz. The total output power of the source did not exceed 0.01 mW. The signal was transmitted through a monochromator and synchronously detected with a semiconductor detector and a lock-in amplifier. The synchronous detection allowed us to filter out the amplified spontaneous emission (ASE) and to measure the small-signal gain by comparing the magnitudes of the signal spectral components at the fiber input and output. In the alternative configuration shown in Fig. 1b, a semiconductor laser diode with a fiber output operating at the wavelength of 1460.5 nm was used as a signal source. The signal amplified in the Bi-doped fiber was separated from the pump radiation with a wavelength-division multiplexer. It was possible to adjust the output power of the laser diode in the range from 0 to 100 mW.

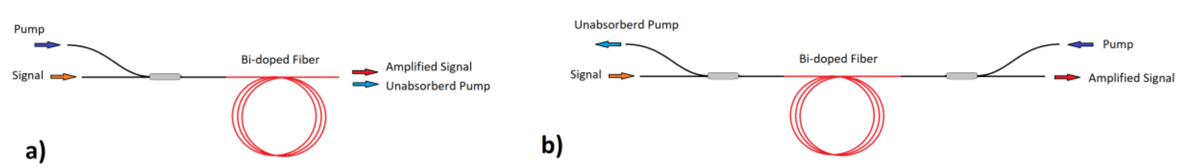


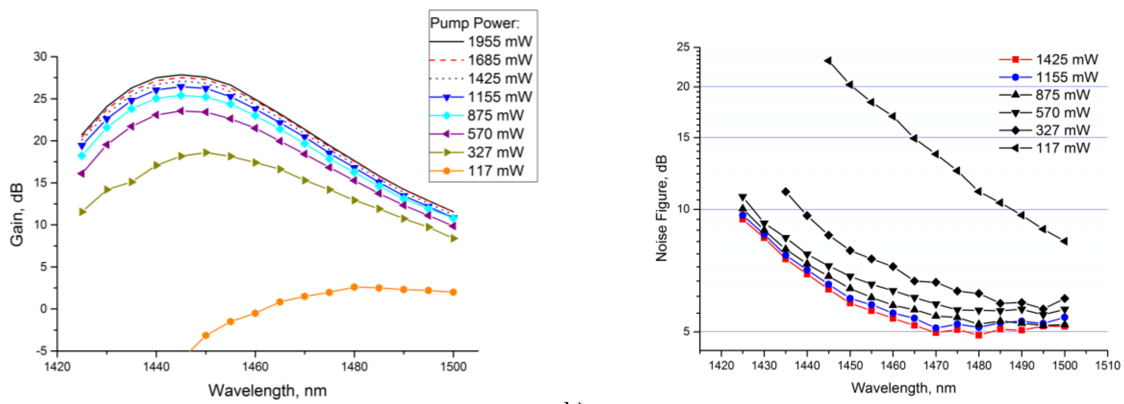
Fig.1. Schematic of the experiments.

In all cases, the output fibers were angle-cleaved to prevent parasitic lasing. The noise figure was measured here only for small signals. ASE magnitudes measured without a signal were used in calculations under assumption that the signal does not influence the population of the excited state of the gain medium (non-depleted operation regime).

3. Results and Discussion

3.1 Amplification of the broadband light signal with the 1350-nm optical pump source

The small-signal optical gain recorded with the broadband light source and 1350-nm optical pump is shown in the Fig. 2a. The amplifier clearly operated in the gain-saturated mode when the pump power exceeded 1 W. The gain reached its maximum of 27.9 dB at the wavelength of 1445 nm at the pump power of ~ 2W, and exceeded 10-dB level in all the studied range with the minimum of 11.6 dB at the wavelength of 1500 nm. 20-dB level was reached in the range of 1425-1475 nm. Pump power decrease down to ~1.1 W resulted in an insignificant gain reduction by 0.7-1.5 dB across the spectrum. The ASE was stronger than the signal and negligibly small (< 1 mW) as compared to the pump powers in the absence of the signal. Therefore, the approximation of a small signal was valid. The noise figure calculated in this approximation is shown in Fig. 2b. The lowest noise figure of nearly 5 dB was observed in the range of 1470-1500nm at the pump powers higher than 1 W. Its magnitude was equal to or lower than 6 dB in the whole range of 1450-1500 nm. The noise figure amounted to 6.4 dB at the position of the optical gain spectral maximum (1445 nm) and tended to increase at shorter wavelengths. This phenomenon could be produced by the OH-groups absorption band peaked at 1380 nm. The tail of this band could interfere with the optical gain of the Bi-doped fiber. Unsaturable optical loss reported earlier [2] could also contribute to the growth of the noise figure.

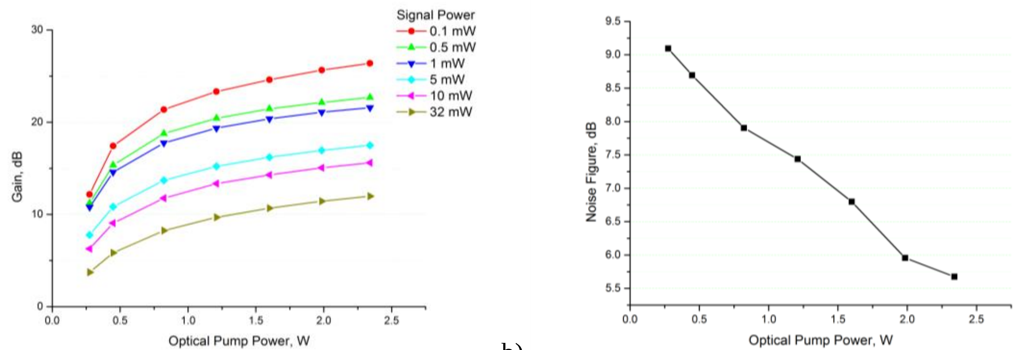


a) b)

Fig.2. Small-signal optical gain observed with 1350-nm pump (a), and noise figure (b).

3.2 Amplification of the spectrally narrow signal at 1460.5 nm with the 1330-nm optical pump source

The use of the laser diode with the adjustable optical power allowed us to study the dependence of the optical gain on the signal intensity, Fig. 3a. The maximum optical gain amounted to 26.4 dB was observed for the input signal with the lowest power of 0.1 mW amplified up to 43.4 mW. It was slightly higher as compared to the optical gain of 24.9 dB obtained previously for this wavelength (see Fig. 2a). This is somewhat expected because the change of the pump wavelength allows to produce higher population of the excited state due to change of the ratio of the absorption and emission cross-sections. The unabsorbed optical power amounted to 850 mW. At other pump powers, it was also noticeably higher than the signal output power justifying the small-signal approximation. The noise figure estimated under this assumption is shown in Fig. 4b. It amounted to 5.7 dB at the highest pump power, which was in a good agreement with the lowest noise figure magnitude of 5.4 dB obtained at this wavelength in the previous case. The situation with a slightly higher gain and, at the same time, a higher noise figure could be attributed to the backward pumping in contrast to the forward pumping used in the previous case. It is worth noting that the estimation of the noise figure with ASE recorded in the absence of the signal provides the upper bound, i.e. a more accurate estimation can only decrease the noise figure, making the demonstrated results even more interesting. Moreover, a clear tendency for the noise figure reduction with the pump power increase is observed in the Fig. 3a, i.e. the noise figure can be further suppressed at a higher pump power. Besides, the optical gain didn't reach a plateau in our experiments in spite of the well-pronounced saturation at high pump powers, Fig. 3a.



a) b)

Fig.3 Optical gain at the wavelength of 1460.5 nm observed with 1330-nm optical pump (a), and noise figure (b).

The lowest gain was observed for the most intensive 32-mW input signal. At the highest pump power of 2.34 W, the observed 12-dB amplification resulted in 505 mW of the output power. Taking into account the unabsorbed pump power of 496 mW, the efficiency of the energy extraction amounts to 27%. In other words, the Bi-doped amplifiers can be efficient and can provide a high gain with a low noise figure in the wavelength range adjacent to the conventional EDFAs operational spectral area. In this work, we managed to shift the gain maximum from 1430 to 1445 nm with its overall noticeable increase at longer wavelengths as compared to the previous results [6]. Moreover, the noise figure was improved reaching the typical values for the EDFAs. In this work, we used relatively high pump powers due to the large fiber core. Manufacturing of a similar fiber with a core diameter of 6 μm would allow the 4-fold reduction of the maximum optical pump power down to the 500-mW level, which is planned for future. At the same time, the amplifier presented here can be used as a booster for amplification of intensive signals or when the nonlinear processes during amplification should be suppressed.

4. Conclusion

In this work, we demonstrated the Bi-doped fiber amplifier optically pumped at the wavelengths of 1330 and 1350 nm, and operating in the range of 1425-1500 nm with the maximum optical gain of 27.9 dB, and the lowest noise figure of ~5 dB. At the wavelength of 1460.5 nm, the maximum output power reached 505 mW with energy extraction efficiency of 27%. Further optimization and improvement of the technology of the Bi-doped fibers will lead to the development of highly efficient and relatively low-noise optical fiber amplifiers, which can be naturally integrated with the existing EDFAs operating in the adjacent spectral area. We anticipate that these results might be of interest for expansion of the operational spectral range of modern optical networks.

Acknowledgement

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